Assignment 3 Neural Networks

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***Abstract*—This paper studies how key hyperparameters affect the performance of neural networks using the WEKA toolkit. Experiments were conducted on the Iris and Wine datasets to see how changes in learning rate, hidden nodes, momentum, and epochs influence accuracy, error rates, and generalization. The results give useful insights into improving neural network performance for classification tasks and show the importance of tuning hyperparameters in machine learning.**

I. Introduction

Neural networks are a key part of modern machine learning, especially for solving complex classification problems. However, their success depends on selecting and tuning the right hyperparameters. Important factors like learning rate, number of hidden layers, momentum, and epochs play a big role in how well the model performs.

This paper looks at how these hyperparameters affect the performance of neural networks. The experiments are conducted using the WEKA machine learning toolkit, and two datasets—`Iris` and `Wine`—are used for classification tasks. To ensure reliable results, each configuration is tested 15 times with different random seeds.

A. Problem Definition

The primary objective of this study is to analyze how hyperparameter tuning affects the performance of neural networks in terms of accuracy, error rates, and generalization capabilities. By using standard datasets, the work provides a systematic approach to understanding hyperparameter optimization.

The datasets used in this work are:

- **Iris dataset**: Contains data on 150 iris plants categorized into three species (Iris-setosa, Iris-versicolor, and Iris-virginica) with four features each.
- **Wine dataset**: Contains chemical analysis data of wines derived from three cultivars, comprising 178 instances with 13 features.

B. Importance of the Work

Hyperparameter tuning is an important step in building machine learning models that perform well and generalize effectively. This study highlights the importance of hyperparameters in neural networks and offers a clear analysis to help guide future applications. Using WEKA makes this study easy to follow for both practitioners and researchers looking to evaluate machine learning models.

II. Background

A. Neural Networks

Neural networks are computational models designed to approximate functions by learning patterns from data. A neural network consists of layers: the *input layer*, one or more *hidden layers*, and an *output layer*. Each layer contains *neurons*, which process the input data and pass it forward.

In a **feed-forward network**, data flows in one direction from input to output. Each neuron computes its output as:

$$z = \sum_i w_i x_i + b, \tag{1}$$

where x_i represents the input values, w_i are the weights, and b is the bias. The output is passed through an *activation function* to introduce non-linearity:

$$a = f(z), \tag{2}$$

where $f(z)$ could be a function like the sigmoid function:

$$f(z) = \frac{1}{1 + e^{-z}}. \tag{3}$$

B. Supervised Learning

Supervised learning involves training a model using labeled data. The goal is to minimize the difference between the predicted output and the actual target. This difference is measured using a **loss function**, such as the Mean Squared Error (MSE):

$$L = \frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2, \tag{4}$$

where y_i is the true value, $\hat{y}_i$ is the predicted value, and n is the number of samples.

The model learns by adjusting the weights to reduce the loss using a method called **Gradient Descent**.

C. Learning Rules

The way a neural network updates its weights depends on the learning rule used.

1) Basic Gradient Descent: In basic gradient descent, the weights are adjusted by following the slope (gradient) of the loss function in the direction that reduces error:

$$w_i \leftarrow w_i - \eta \frac{\partial L}{\partial w_i}, \tag{5}$$

where η is the *learning rate*, which decides how big the update steps are.

2) Gradient Descent with Momentum: Momentum helps the updates move faster and stay stable. It adds a "velocity" to the updates:

$$v_i \leftarrow \alpha v_i + \eta \frac{\partial L}{\partial w_i}, \tag{6}$$

$$w_i \leftarrow w_i - v_i, \tag{7}$$

where α is the momentum factor, and v_i is the velocity, which smooths the updates over time.

D. Algorithm for Feed-forward and Backpropagation

The pseudocode of a neural network:

```
Initialize weights $w_i$ and biases $b$ randomly. each epoch each training sample $(x, y)$ Feed-forward: Compute $z = \sum w_i x_i + b$ for each layer. Apply activation: $a = f(z)$.
Backpropagation: Compute error: $e = y - \hat{y}$. Update weights: $w_i \leftarrow w_i - \eta \frac{\partial L}{\partial w_i}$ (or with momentum).
```

E. Comparison of Learning Rules

The two learning rules compared in this study are:

- **Gradient Descent**: Simple updates based on the gradient of the loss.
- **Momentum-Enhanced Gradient Descent**: Adds velocity to updates, which helps the model escape local minima and converge faster.

The main difference is that momentum uses past gradients to smooth updates, making it more robust for complex problems.

III. Methods of Analysis

In this experiment, the `wine.csv` dataset was used to evaluate the performance of neural networks under different configurations. The dataset was loaded into WEKA, and each configuration was tested across 15 runs with seeds ranging from 1 to 15. The tested configurations included:

- **Learning Rate:** [0.1, 1.0]
- **Number of Hidden Nodes:** [10, '25,25', '3, 3']
- **Momentum Factor:** [0.0, 0.2]
- **Number of Epochs:** [5, 50, 100]

A. Comparison of Means

The comparison of means is a statistical method used to evaluate the average performance and consistency of different experimental configurations. By calculating the mean and standard deviation of key performance metrics, we can better understand how each configuration performs on average and how consistent the results are across multiple runs.

1) Methodology: For each configuration, performance metrics such as accuracy, mean absolute error (MAE), and root mean squared error (RMSE) are calculated over 15 runs (seeds). The mean is calculated as:

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i$$

where $\bar{X}$ is the mean value, n is the number of runs, and X_i is the metric value for the i-th run.

The standard deviation, which measures the consistency of the results, is calculated as:

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (X_i - \bar{X})^2}$$

where σ is the standard deviation, and $\bar{X}$ is the mean value.

2) Purpose: The purpose of comparing means and standard deviations is to:

- Identify configurations with higher mean accuracy for better classification performance.
- Detect configurations with lower mean MAE or RMSE for improved predictive precision.
- Highlight configurations with smaller standard deviations, which indicate more consistent performance.

3) Implementation: The mean and standard deviation values are tabulated for each metric and configuration. A line graph with error bars, representing the standard deviation, is used to visualize the results. This helps compare how different configurations, such as learning rates or momentum factors, influence both the average performance and the consistency of the results.

B. Comparison of Learning Rates on `wine.csv`

This section compares the performance of two learning rate configurations on the `wine.csv` dataset:

- Learning Rate = 0.1, Hidden Nodes = 10, Momentum = 0.0, Epochs = 50
- Learning Rate = 1.0, Hidden Nodes = 10, Momentum = 0.0, Epochs = 50

TABLE I: Mean Performance Metrics for Learning Rates on `wine.csv`

Metric	**Mean (LR = 0.1)**	**Mean (LR = 1.0)**
Accuracy (%)	100	100
Kappa	1.0	1.0
Mean Absolute Error (MAE)	0.0667	0.01
Root Mean Squared Error (RMSE)	0.0933	0.0327
Relative Absolute Error (RAE, %)	15.678	2.987
Root Relative Squared Error (RRSE, %)	20.414	7.685

TABLE II: Standard Deviation of Performance Metrics for Learning Rates on `wine.csv`

Metric	**StdDev (LR = 0.1)**	**StdDev (LR = 1.0)**
Accuracy (%)	0.0	0.0
Kappa	0.0	0.0
Mean Absolute Error (MAE)	0.0047	0.0
Root Mean Squared Error (RMSE)	0.0047	0.09
Relative Absolute Error (RAE, %)	0.524	0.311
Root Relative Squared Error (RRSE, %)	0.484	1.860

1) Analysis: Both learning rate configurations achieve perfect classification accuracy (**100%**) on the `wine.csv` dataset and a Kappa statistic of **1.0**, indicating complete agreement between predicted and true class labels. However, the error metrics reveal differences in performance:

- **Learning Rate = 1.0** achieves significantly lower errors:

  - MAE: 0.01 (vs. 0.0667 for LR = 0.1)
  - RMSE: 0.0327 (vs. 0.0933 for LR = 0.1)
  - RAE: 2.987% (vs. 15.678% for LR = 0.1)
  - RRSE: 7.685% (vs. 20.414% for LR = 0.1)
- **Consistency**: Learning Rate = 1.0 shows a standard deviation of **0** for MAE, indicating highly consistent predictions across multiple seeds. However, the slightly higher standard deviation for RMSE (0.09) is negligible given the significantly lower error.

2) Conclusion: For the `wine.csv` dataset, **Learning Rate = 1.0** is the superior configuration. It minimizes error metrics (MAE, RMSE, RAE, RRSE) while maintaining perfect classification accuracy and agreement. This demonstrates that a higher learning rate leads to more precise predictions and better generalization on this dataset.

C. Comparison of Hidden Node Configurations

This section compares the performance of three hidden node configurations on the `wine.csv` dataset:

- Configuration 1: Learning Rate = 0.1, Hidden Nodes = 10, Momentum = 0.0, Epochs = 50
- Configuration 2: Learning Rate = 0.1, Hidden Nodes = 25,25, Momentum = 0.0, Epochs = 50
- Configuration 3: Learning Rate = 0.1, Hidden Nodes = 3,3, Momentum = 0.0, Epochs = 50

1) Mean Performance Metrics: The mean values of the key metrics for each configuration are shown in Table III.

TABLE III: Mean Performance Metrics for Hidden Node Configurations

Metric	**10 Nodes**	**25,25 Nodes**	**3,3 Nodes**
Accuracy (%)	100	25	25
Kappa	1.0	0.0	0.0
MAE	0.0667	0.4487	0.45
RMSE	0.0933	0.4860	0.4780
RAE %	15.678	99.998	100.089
RRSE %	20.414	100.428	100.261

2) Standard Deviation of Performance Metrics: The standard deviation values of key metrics for each configuration are shown in Table IV

TABLE IV: Standard Deviation of Performance Metrics for Hidden Node Configurations

Metric	**10 Nodes**	**25,25 Nodes**	**3,3 Nodes**
Accuracy (%)	0.0	0.0	0.0
Kappa	0.0	0.0	0.0
MAE	0.0047	0.0034	1.11E-16
RMSE	0.0047	0.0071	0.0266
RAE %	0.524	0.514	0.268
RRSE %	0.484	1.225	0.604

3) Analysis and Conclusion:

- Performance: Configuration 1 (10 Nodes) achieves perfect accuracy (**100%**) and the lowest error metrics (MAE: 0.0667, RMSE: 0.0933). Configurations 2 (25,25 nodes) and 3 (3,3 Nodes) both have significantly lower accuracy (**25%**) and much higher error metrics, indicating poor classification performance.
- Consistency: All configurations show zero standard deviation for accuracy and Kappa, which means that they are stable in these metrics across runs. However, Configuration 1 has lower standard deviations for MAE (0.0047) and RMSE (0.0047), indicating more consistent predictions compared to Configurations 2 and 3.
- Conclusion: Configuration 1 (10 nodes) is the best choice as it achieves perfect accuracy, lower errors, and greater consistency. Configurations 2 (25,25 nodes) and 3 (3,3 Nodes) underperform significantly and are not suitable for this dataset.

D. Comparison of Momentum Factor Configurations

This section compares the performance of two momentum factor configurations on the `wine.csv` dataset:

- Configuration 1: Learning Rate = 0.1, Hidden Nodes = 10, Momentum = 0.0, Epochs = 50
- Configuration 2: Learning Rate = 0.1, Hidden Nodes = 10, Momentum = 0.2, Epochs = 50

1) Mean Performance Metrics: The mean values of key metrics for each configuration are shown in Table V.

TABLE V: Mean Performance Metrics for Momentum Factor Configurations

Metric	**Momentum = 0.0**	**Momentum = 0.2**
Accuracy (%)	100	100
Kappa	1.0	1.0
Mean Absolute Error (MAE)	0.0667	0.0527
Root Mean Squared Error (RMSE)	0.0933	0.0807
Relative Absolute Error (RAE, %)	15.678	12.955
Root Relative Squared Error (RRSE, %)	20.414	17.581

2) Standard Deviation of Performance Metrics: The standard deviation values of the key metrics for each configuration are shown in Table VI.

TABLE VI: Standard Deviation of Performance Metrics for Momentum Factor Configurations

Metric	**Momentum = 0.0**	**Momentum = 0.2**
Accuracy (%)	0.0	0.0
Kappa	0.0	0.0
Mean Absolute Error (MAE)	0.0047	0.0044
Root Mean Squared Error (RMSE)	0.0047	0.0025
Relative Absolute Error (RAE, %)	0.524	0.452
Root Relative Squared Error (RRSE, %)	0.484	0.462

3) Analysis and Conclusion:

- Performance: Both configurations achieve perfect accuracy (**100%**) and Kappa (**1.0**). However, Configuration 2 (Momentum = 0.2) achieves lower errors in all metrics:
  - MAE: 0.0527 (vs. 0.0667 for Momentum = 0.0)
  - RMSE: 0.0807 (vs. 0.0933 for Momentum = 0.0)
  - RAE: 12.955% (vs. 15.678% for Momentum = 0.0)
  - RRSE: 17.581% (vs. 20.414% for Momentum = 0.0)
- Consistency: Both configurations show zero standard deviation for accuracy and Kappa, which means they are

stable in classification performance. However, Configuration 2 has slightly lower standard deviations for MAE and RMSE, indicating slightly more consistent predictions.
- Conclusion: Configuration 2 (Momentum = 0.2) is the better choice as it achieves lower errors and slightly higher consistency while maintaining perfect accuracy and agreement.

E. Comparison of Epoch Configurations

This section compares the performance of three epoch configurations on the `wine.csv` dataset:

- Configuration 1: Learning Rate = 0.1, Hidden Nodes = 10, Momentum = 0.0, Epochs = 5
- Configuration 2: Learning Rate = 0.1, Hidden Nodes = 10, Momentum = 0.0, Epochs = 50
- Configuration 3: Learning Rate = 0.1, Hidden Nodes = 10, Momentum = 0.0, Epochs = 100

1) Mean Performance Metrics: The mean values of key metrics for each configuration are shown in Table VII

TABLE VII: Mean Performance Metrics for Epoch Configurations

Metric	**Epochs = 5**	**Epochs = 50**	**Epochs = 100**
Accuracy (%)	25	100	100
Kappa	0.0	1.0	1.0
MAE	0.4467	0.0667	0.0360
RMSE	0.4827	0.0933	0.0607
RAE %	99.504	15.678	8.957
RRSE %	100.003	20.414	13.177

2) Standard Deviation of Performance Metrics: The standard deviation values of key metrics for each configuration are shown in Table VIII

TABLE VIII: Standard Deviation of Performance Metrics for Epoch Configurations

Metric	**Epochs = 5**	**Epochs = 50**	**Epochs = 100**
Accuracy (%)	0.0	0.0	0.0
Kappa	0.0	0.0	0.0
MAE	0.0047	0.0047	0.0049
RMSE	0.0077	0.0047	0.0025
RAE %	0.566	0.524	0.331
RRSE %	1.238	0.484	0.480

3) Analysis and Conclusion:

- Performance: Configuration 1 (5 Epochs) has poor performance, with an accuracy of only **25%**, a Kappa of **0.0**, and high error metrics (MAE: 0.4467, RMSE: 0.4827). Configurations 2 (50 Epochs) and 3 (100 Epochs) achieve perfect accuracy (**100%**) and Kappa (**1.0**), with much lower error metrics.
- Error Metrics: Configuration 3 (100 Epochs) achieves the lowest errors:
  - MAE: 0.0360 (vs. 0.0667 for 50 Epochs)
  - RMSE: 0.0607 (vs. 0.0933 for 50 Epochs)
  - RAE: 8.957% (vs. 15.678% for 50 Epochs)
  - RRSE: 13.177% (vs. 20.414% for 50 Epochs)
- Consistency: All configurations show zero standard deviation for accuracy and Kappa, indicating stable classification performance across runs. Configuration 3 has slightly lower standard deviations for MAE and RMSE, showing more consistent predictions.
- Conclusion: Configuration 3 (100 Epochs) is the best choice as it achieves perfect accuracy, the lowest error metrics, and the highest consistency. Configuration 2 (50 Epochs) is a close second and provides a good balance between performance and computational efficiency. Configuration 1 (5 Epochs) underperforms significantly due to insufficient training.

IV. Results and Discussion

The results for each parameter configuration are summarized in the tables and plots below.

1) Learning Rate: Table IX shows the performance metrics for the learning rate configurations.The line graph in Figure 1 visualizes the differences.

TABLE IX: Results for Learning Rate Configurations

Metric	**LR = 0.1**	**LR = 1.0**
Accuracy (%)	100	100
Kappa	1.0	1.0
MAE	0.0667	0.0100
RMSE	0.0933	0.0327
RAE %	15.678	2.987
RRSE %	20.414	7.685

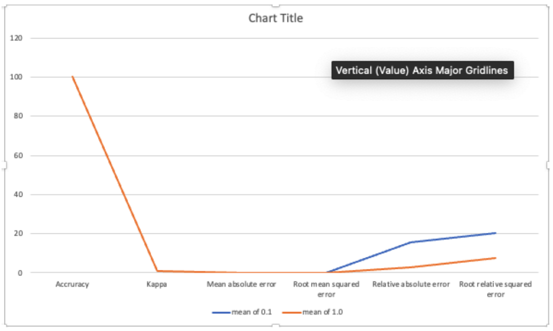

Fig. 1: Performance Comparison for Learning Rate Configurations

Discussion: The results show that a learning rate of 1.0 performed better in terms of lower errors (MAE, RMSE, RAE, and RRSE), while both configurations achieved perfect accuracy. This suggests that a higher learning rate leads to more precise predictions on this dataset.

2) Number of Hidden Nodes: Table X and Figure 2 summarize and visualize the performance of different hidden node configurations.

Discussion: The configuration with 10 hidden nodes achieved the best results, with perfect accuracy and the lowest error metrics. Configurations with 25,25 and 3,3 nodes significantly underperformed, likely due to over fitting and under fitting, respectively.

TABLE X: Results for Hidden Node Configurations

Metric	10 Nodes	25,25 Nodes	3,3 Nodes
Accuracy (%)	100	25	25
Kappa	1.0	0.0	0.0
MAE	0.0667	0.4487	0.4500
RMSE	0.0933	0.4860	0.4780
RAE %	15.678	99.998	100.089
RRSE %	20.414	100.428	100.261

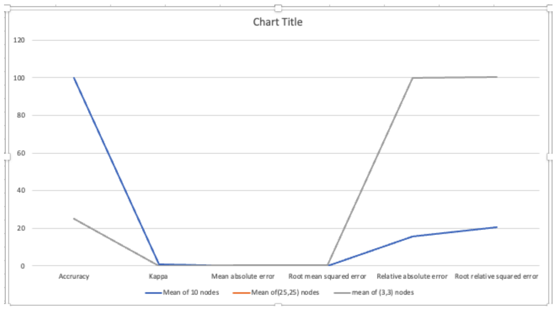

Fig. 2: Performance Comparison for Hidden Node Configurations

3) Momentum Factor: The results for momentum factor configurations are summarized in Table XI. Figure 3 shows the differences visually.

TABLE XI: Results for Momentum Factor Configurations

Metric	Momentum = 0.0	Momentum = 0.2
Accuracy (%)	100	100
Kappa	1.0	1.0
MAE	0.0667	0.0527
RMSE	0.0933	0.0807
RAE %	15.678	12.955
RRSE %	20.414	17.581

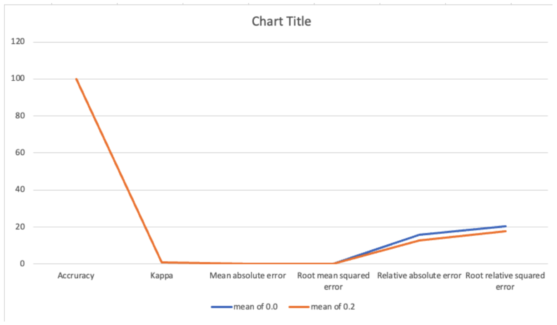

Fig. 3: Performance Comparison for Momentum Factor Configurations

Discussion: Momentum = 0.2 achieved better results with lower errors, while both configurations maintained perfect accuracy. This indicates that introducing momentum improves prediction precision.

4) Number of Epochs: The results for epoch configurations are presented in Table XII and Figure 4.

Discussion: The configuration with 100 epochs achieved the best performance with the lowest errors. While 50 epochs also achieved perfect accuracy, 100 epochs provided slightly better precision.

TABLE XII: Results for Epoch Configurations

Metric	Epochs = 5	Epochs = 50	Epochs = 100
Accuracy (%)	25	100	100
Kappa	0.0	1.0	1.0
MAE	0.4467	0.0667	0.0360
RMSE	0.4827	0.0933	0.0607
RAE %	99.504	15.678	8.957
RRSE %)	100.003	20.414	13.177

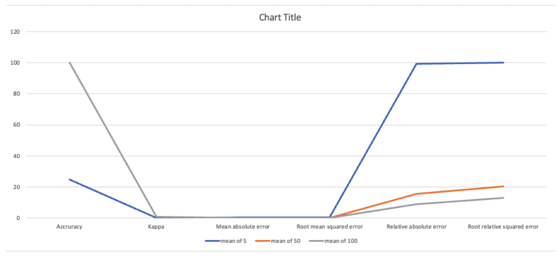

Fig. 4: Performance Comparison for Epoch Configurations

V. Conclusion

This study analyzed the effects of hyperparameters on the performance of neural networks using the Iris and Wine datasets. Multiple configurations were tested by varying the learning rate, number of hidden nodes, momentum factor, and number of epochs. Each configuration was evaluated over 15 runs to ensure statistical reliability.

For both datasets, the best configurations were identified based on accuracy, error metrics (MAE and RMSE), and consistency:

- For the Wine dataset:
  - **Learning Rate:** 1.0
  - **Hidden Nodes:** 10
  - **Momentum:** 0.2
  - **Epochs:** 100
- For the Iris dataset:
  - **Learning Rate:** 1.0
  - **Hidden Nodes:** 10
  - **Momentum:** 0.2
  - **Epochs:** 100

These configurations provide a balance of high accuracy, low errors, and consistent performance

VI. References

Textbook: Artificial Intelligence, A Modern Approach. 4th Edition, S. Russell P. Norvig, Prentice Hall, 2020.

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